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Effects of fertilization on growth of 30-year-old lodgepole pine in west-central Alberta

R. C. Yang

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LODGEPOLE PINE IN WEST-CENTRAL ALBERTA**

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ABSTRACT

N, P, and S were applied to two 30-year-old lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stands in west-central Alberta. Results after 10-year fertilization showed that on Coalspur soils, N improved tree diameter increment and tree volume increment throughout the range of 76–300 kg/ha of N. On Mercoal soils, the responses to N were not as strong as those on Coalspur; S showed a significant improvement in diameter increment, but both N (up to 188 kg/ha) and S (up to 56 kg/ha) improved volume increment. Improvements in diameter increment were as high as 109% (1.3–2.6 cm) on the Coalspur soils and 70% (1.6–2.7 cm) on the Mercoal soils. Improvements in volume increment of dominant and codominant trees were up to 40% in both stands. Stand volume increments were not statistically significant because of high and variable mortality. This suggests that thinning should precede fertilization in dense stands.

RESUME

Des peuplements de pins tordus latifoliés (*Pinus contorta* Dougl. var. *latifolia* Engelm.) de 30 ans, du centre-ouest de l'Alberta, ont été traités au moyen de N, de P et de S. Après 10 ans de fertilisation, les résultats ont montré que, à Coalspur, N avait amélioré la croissance en diamètre et en volume des arbres dans la gamme de 76 à 300 kg/ha. À Mercoal, la réaction n'a pas été si forte; S a donné une augmentation notable de la croissance en diamètre, mais N (jusqu'à 188 kg/ha) et S (jusqu'à 56 kg/ha) ont amélioré la croissance en volume. L'amélioration de la croissance en diamètre a atteint 109% (de 1.3 à 2.6 cm) à Coalspur et 70% (de 1.6 à 2.7 cm) à Mercoal. L'augmentation de la croissance en volume des arbres dominants et codominants a atteint 40% dans les deux peuplements. L'augmentation de volume des peuplements n'a pas été statistiquement significative à cause d'une mortalité élevée et variable. Cette observation porte à croire qu'avant de fertiliser les peuplements denses, il faudrait les soumettre à une coupe d'éclaircie.

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NOTE

The exclusion of certain manufactured products does not imply rejection nor does the mention of other products imply endorsement by the Canadian Forestry Service.

INTRODUCTION

Correct diagnosis of the nutrient requirements of a forest stand is a prerequisite for effective fertilization, and a timely application of needed nutrients maximizes stand yields. The timing of forest fertilization has strong physiological and economic implications. Fertilizing pre-harvest stands has obvious financial appeal (Miller and Fight 1979); because young stands are generally more responsive to management manipulations, fertilizing young stands could be a viable management alternative.

Nitrogen (N) fertilization increased lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) growth (Boyd et al. 1975; Cochran 1975, 1979; Bella 1978; Yang 1983b, 1985), but phosphorus (P) fertilization had little influence on tree growth of this species. The effect of sulfur (S), on the other hand, remains unclear. Because of wide areas of S deficiency in the United States (Beaton et al. 1971), particularly in the Pacific northwest (Will and Youngberg 1978), nutritional studies on forest tree growth response to S fertilization have been undertaken (Turner 1979).

Effects of N, P, and S on tree growth have been reported for some conifers in the Pacific northwest. After a thorough study of many Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) fertilizer trials on Vancouver Island, Bartlett (1977) concluded that response to $N \times S$, $N \times P \times S$, and $N \times P \times K$ combinations was common to most experiments and that response to $N \times S$, $N \times P \times S$, and $N \times P \times K$ combinations was often greater than N alone. This was especially true with

respect to $N \times S$ and $N \times P \times S$. The author further inferred that $N \times P \times S$ fertilizer at rates of 321 kg/ha of N, 180 kg/ha of P, and 103 kg/ha of S produced the best results. Will and Youngberg (1978) reported a similar result after applying N, P, and S to a 45-year-old thinned ponderosa pine (*Pinus ponderosa* Laws.) stand in Oregon. A possibly beneficial effect of S was also observed by Cochran (1978) on a thinned ponderosa pine stand where S increased volume production more than 0.7 m³ per year over treatment of N alone. Sulfur deficiency in some central Oregon pumice soils was conclusively demonstrated by Will and Youngberg (1978) in a pot bioassay of Monterey pine (*Pinus radiata* D. Don.) seedlings. The study showed seedlings receiving $N \times P \times S$ nutrients outgrew, in 18 out of 22 soils, those receiving only $N \times P$ nutrients by 130–1100% in total weight after a 6-month growth period.

Because of possible S deficiency in luvisols of west-central Alberta, a field trial was initiated in 1971 to ascertain growth response of lodgepole pine to N, P, and S fertilization. The study was carried out in stands of two age classes (30- and 70-year-old) on two common luvisols in west-central Alberta. Yang (1985) summarized 10-year results in the 70-year-old stands, where improvements in stand productivity as high as 50% were achieved. The present report summarizes 10-year growth response of the 30-year-old stands to N, P, and S fertilization.

METHODS

Description of study areas

The study areas were located southeast of Hinton, Alberta (53°25'N, 117°34'W), on the St. Regis (Alberta) Ltd. lease area. Forests in these areas are within the Lower Foothills Section (B.19a) of the Boreal Forest Region (Rowe 1972). Two fully stocked 30-year-old lodgepole pine stands of fire origin were selected, one on Coalspur soil and one on Mercoal soil.

The Coalspur stand was situated in the Wampus Creek area (Legal Subdivisions 10- and 11-8-48-23-W6), approximately 70 km southeast of Hinton. Soils were predominantly Orthic Gray Luvisols with some Brunisolic Gray Luvisols developed in Cordilleran till and

weathered sandstone, respectively. Topography ranged from rolling to hilly (24–45% slope) with a southern to westerly aspect. Soils were well-drained.

Ground cover of the Coalspur stand varied from sparse to dense, depending on the density of overtopping lodgepole pine. Lesser vegetation included Labrador tea (*Ledum groenlandicum* Oeder), bunchberry (*Cornus canadensis* L.), wild rose (*Rosa acicularis* Lindl.), mountain ash (*Sorbus* spp.), and bog cranberry (*Vaccinium vitis-idaea* L. var. *minus* Lodd), with a sporadic occurrence of white spruce (*Picea glauca* (Moench) Voss) and alpine fir (*Abies lasiocarpa* (Hook.) Nutt.) regeneration. A heavy deadfall resulted from the dense stand condition. The vegetation of the

Table 1. Coded levels and rates of fertilizers¹ used in the study

Treatment	Factorial design	Coded level			Nutrient (kg/ha)		
		N	P	S	N	P	S
1	1	-1	-1	-1	76	38	23
2	1	1	-1	-1	300	38	23
3	1	-1	1	-1	76	150	23
4	1	1	1	-1	300	150	23
5	1	-1	-1	1	76	38	90
6	1	1	-1	1	300	38	90
7	1	-1	1	1	76	150	90
8	1	1	1	1	300	150	90
9 ²	0	-1.68	0	0	0	94	56
11	0	0	-1.68	0	188	0	56
13	0	0	0	-1.68	188	94	0
15-20	0	0	0	0	188	94	56
21	0	0	-1.68	-1.68	188	0	0
22 ²	0	-1.68	0	-1.68	0	94	0
23	0	-1.68	-1.68	0	0	0	56
24	0	-1.68	-1.68	-1.68	0	0	0

¹ Nutrient sources: Nitrogen—urea (46-0-0) and ammonium phosphate (11-55-0).
Phosphorus—ammonium phosphate (11-55-0).
Sulfur—elemental sulfur (0-0-100).

² Triple superphosphate (9-45-0) used.

study area was described as *Pinus contorta*-*Picea mariana*/*Ledum groenlandicum*/*Pleurozium schreberi*¹.

The Mercoal stand was located in the New Road area (Legal Subdivisions 6- and 7-5-49-22-W6), approximately 50 km southeast of Hinton. Soils of the study area were Podzolic Gray Luvisols of the Mercoal series under the Robb association (Dumanski et al. 1972). In contrast to the Coalspur stand, the topography of this area ranged from level to undulating (4-11% slope). The soils were well-drained.

A dense ground cover consisted of Labrador tea, bearberry (*Arctostaphylos uva-ursi* Spreng), bunchberry, alder (*Alnus* spp.), willow (*Salix* spp.), and fireweed (*Epilobium angustifolium* L.). Alpine fir and white spruce regeneration were also sporadically present. The ecological association of this area was similar to that of the Coalspur site.

Experimental design and plot layout

A second-order central composite rotatable design (Cochran and Cox 1957) was selected for this study to provide a general predictive relationship between tree and stand responses and fertilizer levels. A detailed description of the experimental design was presented by Yang (1985). Because of the inadequacy of the central composite design in approximating tree and stand responses to fertilization (Yang 1983a, 1985), this study analyzed only treatments in Factorials 0 and 1 series (Table 1) that were incorporated in the central composite design.

Each study area was divided into three blocks containing 24 circular plots of 3.57-m radius (0.004 ha). The plot centers were established systematically on a square grid at about 20-m (1.0-chain) intervals. If a plot center fell in an abnormally open portion of the stand, the plot was omitted or moved to an adjacent fully stocked portion of the stand. The plot centers were marked with

¹ Personal communication from R.M. Annas and I.G.W. Corns, 1983.

an aluminum post and 10 thrifty trees closest to the plot center were tagged. Plot boundaries were marked with paint. Fertilizer treatments were randomly assigned to each plot within the block.

Soil and foliar analysis

A series of soil sampling points was established at each study area (13 at the Coalspur site and 12 at the Mercoal site) and information was obtained on soil horizon description, horizon thickness, parent material, penetrometer reading, N, P, K, Na, Ca, and Mg contents, pH, percent organic matter, and percent carbon. In addition, slope grade, slope position, and aspect were also recorded for each soil pit. Procedures for determining soil chemical properties were described by Yang (1985).

Foliar samples of the current year's growth on the uppermost lateral branches of three dominant trees per plot were gathered in the fall of 1971. Total N, available P, and S in foliage were determined following procedures outlined by Kalra (1971).

Fertilizer application

Urea (46-0-0), ammonium phosphate (11-55-0), triple superphosphate (0-45-0), and elemental sulfur (0-0-100) were the main nutrient sources used in this study. Nitrogen-free treatments were made using the required quantities of triple superphosphate and elemental S, while P-free treatments were prepared by combining the required quantities of urea and S. Because triple superphosphate contains approximately 0.9% S, ammonium phosphate was used whenever possible to minimize the contamination of the S-free treatments by the P source.

The fertilizer combination for each plot was precisely weighed out, bagged, and identified by plot number in the laboratory prior to field application. All fertilizers were applied by a cyclone seeder in mid-May 1972.

Measurement and analysis

Diameter at breast height outside bark (dbhob) of all living trees on each plot was measured at 1.37 m in the fall of 1971. A sufficient number of trees was also measured to construct a reliable height-diameter curve for each area. In June 1981, after 10 growing seasons, dbhob of all living trees in each plot was determined and tallied by species. Ten-year tree diameter increment

(TDI) was determined from the dbhob of the 10 tagged trees. Dead or missing tagged trees were excluded from the analysis.

To accurately determine tree volume increment (TVI) due to fertilization, three dominant or codominant trees were felled on each plot for stem analysis. Disks were obtained at stump (0.3 m), breast height (1.37 m), 3.05 m, 6.1 m, base of live crown, and other positions of major changes in bole shape. Tree volumes before and after fertilization were determined from the stem analysis disks by the Smalian formula. Ten-year TVI were obtained by difference. Total and merchantable stand volumes before and after fertilization were estimated from tree tailings using suitable equations. Stem volume was computed for each tree and summed to obtain stand volumes. Ten-year periodic stand volume increments were estimated by difference.

The following tree volume equations were used (Johnson 1976):

$$1. \text{ Trees } \leq 8.9 \text{ cm } (\leq 3.5 \text{ in.}) \text{ dbhob} \\ V = 0.0232 + 0.00253D^2HT$$

$$2. \text{ Trees } 9.1\text{--}21.6 \text{ cm } (3.6\text{--}8.5 \text{ in.}) \text{ dbhob} \\ V = -0.0949 + 0.00272D^2HT$$

where V, D, and HT denote volume (cu. ft.), dbhob (in.), and tree height (ft.), respectively. Tree height was estimated from the following regressions:

$$HT_c = 2.98 + 12.159D - 1.627D^2$$

$$HT_m = 4.15 + 11.620D - 1.322D^2$$

where HT_c and HT_m are total height (ft.) for trees in the Coalspur and Mercoal sites.

Merchantable volumes, based on a 10.16-cm (4.0-in.) diameter inside bark (dib) top and a 0.30-m (1.0-ft.) stump, were calculated for all trees ≥ 11.68 cm (4.6 in.) dbhob using Honer's (1967) conversion functions for lodgepole pine:

$$X = (4.0/D)^2 \times (1.0 + 1.0/HT)$$

$$VM = V \times (0.9658 - 0.1278X - 0.8108X^2)$$

where VM is the merchantable volume (cu. ft.) and D, HT, and V are as defined above. All measurements and computations were initially performed using Imperial units and were subsequently converted into the SI units.

Table 2. Stand characteristics prior to fertilization

Treatment	Coalspur				Mercoal			
	Stem/ ha	Basal area (m ² /ha)	Total volume (m ³ /ha)	Merchantable volume (m ³ /ha)	Stem/ ha	Basal area (m ² /ha)	Total volume (m ³ /ha)	Merchantable volume (m ³ /ha)
Factorial 0								
Control	14 490	36.17	123.68	5.01	7 240	29.13	116.10	20.72
N188	15 640	25.98	89.53	2.34	9 800	31.28	121.99	7.83
P94	14 160	28.04	97.23	4.31	7 580	27.88	109.96	10.60
S56	13 830	28.52	97.78	3.88	10 790	31.48	122.40	3.54
N188 P94	15 970	26.69	91.85	0.0	12 180	40.31	156.33	18.16
N188 S56	15 640	24.15	83.44	0.0	6 260	27.75	89.77	14.46
P94 S56	15 400	28.70	100.22	0.0	9 550	27.03	104.04	8.56
N188 P94 S56	13 500	27.01	93.81	2.69	9 270	26.08	101.32	5.07
Factorial 1								
N76 P38 S23	14 080	23.28	79.64	3.69	12 600	26.57	99.71	0.0
N300 P38 S23	11 530	29.14	100.39	7.73	9 880	28.92	111.40	13.70
N76 P150 S23	11 530	27.02	93.66	6.97	4 860	20.80	83.54	11.96
N300 P150 S23	12 600	20.50	70.68	0.0	8 070	31.99	126.26	10.22
N76 P38 S90	16 800	24.85	83.83	3.72	13 750	33.95	129.95	8.10
N300 P150 S90	17 870	24.51	85.00	0.0	10 100	29.38	112.23	0.0
N76 P38 S90	22 480	28.29	98.47	0.0	10 280	28.17	107.15	3.98
N300 P150 S90	11 630	28.94	99.41	2.00	9 960	23.82	90.81	0.0
Mean	14 820	26.99	93.04	2.64	9 510	29.03	111.44	8.56

TDI and TVI were subjected to covariance analysis using initial tree diameters and tree volumes, respectively, as the covariates; both TDI and TVI were highly correlated with those initial values. Periodic stand basal area (BA) and stand total volume increments, on the

other hand, were not statistically correlated to initial stand basal areas and volumes, probably because of the high mortality that occurred during the experimental period. These increments were subjected to analysis of variance.

RESULTS AND DISCUSSION

Pretreatment stand conditions

Number of stems, basal area, total volume, and merchantable volume per hectare of the two 30-year-old lodgepole pine stands before fertilization are summarized in Table 2. Generally, Mercoal sites were somewhat more productive than Coalspur sites; the former had higher BA and total and merchantable volumes, while the latter had greater numbers of stems per hectare. Table 2 illustrates the effect of stand density on tree size and merchantable volume; only plots with densities

below 10 000 stems/ha had a noticeable merchantable volume. Judged by yield table values (Smithers 1961; Johnstone 1976), the Coalspur stand appeared to be overly dense.

Soil and foliar analysis

Soil analyses (Table 3) showed similarity in chemical properties for these two luvisols though total N, available P, percents organic matter and carbon, and exchangeable cations of K, Ca, and Mg in the LFH

Table 3. Physiochemical characteristics of Coalspur and Mercoal soils

Horizon		Thick- ness (cm)	pH	Exchangeable cation (μg/g)				% organic matter	% carbon	Available P (μg/g)	Total N (μg/g)
				Na	K	Ca	Mg				
Coalspur											
LFH	Avg.	4.25	4.02	120	1 060	4 426	736	78.3	45.4	212	13 600
	Max.	5.00	5.05	266	1 482	7 286	1 290	98.4	57.1	365	15 915
	Min.	3.00	3.50	64	680	2 344	612	60.3	35.0	135	11 422
Ae	Avg.	11.08	3.54	37	117	764	171	2.9	1.7	30	1 305
	Max.	21.00	3.80	87	164	1 160	265	4.8	2.8	76	2 774
	Min.	9.00	3.25	25	78	310	88	1.6	0.9	9	978
Bt	Avg.	22.00	3.81	35	70	708	253	1.3	0.7	10	847
	Max.	27.00	4.10	81	106	1 038	738	2.3	1.3	20	1 560
	Min.	16.00	3.45	25	47	300	88	0.5	0.3	2	497
C	Avg.	—	3.89	51	82	1 190	362	1.2	0.7	11	910
	Max.	—	4.05	108	106	1 846	665	2.2	1.3	23	1 235
	Min.	—	3.65	28	51	322	184	0.6	0.4	3	429
Mercoal											
LFH	Avg.	4.42	4.25	81	1 988	4 790	897	82.5	47.9	335	14 900
	Max.	6.00	4.55	104	4 125	8 022	1 268	98.5	60.0	636	18 420
	Min.	3.00	4.00	69	931	3 418	649	50.1	29.0	213	9 295
Ae ₁	Avg.	5.17	3.57	35	121	794	95	3.6	2.1	43	1 239
	Max.	7.00	3.80	39	278	1 314	154	8.2	4.7	85	1 903
	Min.	4.00	3.33	30	66	384	52	1.6	0.9	8	651
Bt	Avg.	5.42	4.35	35	86	582	112	3.1	1.8	10	1 217
	Max.	8.00	5.20	39	156	1 380	294	4.5	2.7	20	1 680
	Min.	4.00	3.80	30	47	266	39	1.5	0.9	2	806
Ae ₂	Avg.	9.50	—	—	—	—	—	—	—	—	—
	Max.	14.00	—	—	—	—	—	—	—	—	—
	Min.	6.00	—	—	—	—	—	—	—	—	—
Bt	Avg.	21.09	4.19	35	117	2 316	428	0.6	0.4	23	257
	Max.	24.00	4.45	41	141	3 588	537	0.9	0.5	33	394
	Min.	18.00	3.95	30	94	1 600	306	0.5	0.3	13	68
C	Avg.	—	4.23	37	94	2 194	368	0.6	0.3	23	259
	Max.	—	4.60	46	133	2 986	524	0.8	0.5	35	497
	Min.	—	3.75	32	43	702	146	0.4	0.2	3	189

horizon were consistently higher on the Mercoal than on the Coalspur soils. In Bt and C horizons these exchangeable cations on Mercoal soils exceeded those on Coalspur soils. Despite Mercoal soils having a higher total N content in the LFH horizon, the N contents in Bt and C horizons were considerably lower than those of Coalspur soils.

Analysis of N and P nutritional status of needles before fertilization (Table 4) indicated that foliar N content for trees on both soils was moderately deficient, judged by Swan's (1972) standards. The average foliar N content of trees in the Coalspur stand differed significantly ($p = 0.05$) from that in the Mercoal stand. The lower N content in the Coalspur stand suggested that it might respond to higher rates of N fertilizer.

Table 4. Foliar N, P, and S concentrations in 30-year-old lodgepole pine needles before fertilization

	Coalspur		Mercoal	
	Mean	S.D. ^a	Mean	S.D.
N (%)	1.06	0.0110	1.15	0.0100
P (%)	0.11	0.0094	0.12	0.0011
S ($\mu\text{g/g}$)	452	16.8	439	15.4

^a S.D. = standard error of mean.

In contrast to N, foliar P content of trees before fertilization averaged 0.11% in the Coalspur and 0.12% in the Mercoal stand; the difference was significant at the 5% level. The nutritional status fell within the transition zone of deficiency to sufficiency for this species (Swan 1972). The higher foliar P content in the Mercoal stand might partially reflect a somewhat higher available P in these soils (Table 3). Based on Swan's (1972) standards, one would expect tree growth to be less responsive to P than to N fertilization.

Sulfur content in tree needles was similar and averaged 439 and 452 $\mu\text{g/g}$ for the Mercoal and Coalspur stands. Foliar S is low in comparison with those reported by Beaton et al. (1965) for lodgepole pine in British Columbia. Sulfur content in biological materials is difficult to determine (Turner 1979), so at least part of the difference could be due to analytical procedures.

Tree diameter increment

Nitrogen fertilization improved the 10-year periodic diameter increment of trees on Coalspur soils in both factorial series (Table 5); in addition, the effect of N $\times$ S interactions in the Factorial 0 series was significant at the 5% level. The interaction is illustrated in Figure 1, which shows a depressive effect of S on TDI on Coalspur soils at 188 kg/ha of N. The depressive effect did not appear in the Factorial 1 experiment (Table 5).

In the Coalspur stand, TDI on unfertilized plots averaged 1.3 cm; an application of 188 kg/ha of N increased TDI to 2.6 cm, or 109%. In the Factorial 1 experiment N was the only nutrient that significantly improved TDI on this soil. The beneficial effect of N fertilization is apparent where TDIs of high N plots were consistently higher than those of the low N plots.

In contrast to Coalspur soils, the TDI of trees on Mercoal soils was increased more by S than by N fertilization in the Factorial 0 series. Nitrogen improved TDI, but its effect was only significant at the $p = 0.05$ level. TDI of unfertilized plots averaged 1.6 cm; an addition of 188 kg/ha of N increased TDI to 2.1 cm, whereas an application of 56 kg/ha of S alone improved TDI by 1.0 cm. An application of 188 kg/ha of N, 94 kg/ha of P, and 56 kg/ha of S in combination raised TDI to 2.8 cm or 74% (Table 6). The beneficial interactions of N, P, and S on TDI on Mercoal soils became apparent in the Factorial 1 experiment (Table 5), where all treatments significantly improved TDI. The fertilizer combination of 300 kg/ha of N, 150 kg/ha of P, and 90 kg/ha of S raised TDI by 1.5 cm, or 87%, over that of unfertilized plots.

Tree volume increment

Analyses of periodic TVI on Coalspur soils confirmed that N was the most beneficial nutrient to tree growth (Table 5). In addition to N, the effect of P $\times$ S interactions on TVI was also significant at the Factorial 1 level.

The effect of N on TVI of dominant and codominant trees on Coalspur soils is shown in Table 5. At the Factorial 0 level, only treatments receiving N at 188 kg/ha showed a significant increase in TVI over the control. An increase in N from 0 to 188 kg/ha increased TVI by more than 40% in the 10-year period. That the effect of N on TVI in the Coalspur stand was also significant in the Factorial 1 series implies that an increase of N from 76 to 300 kg/ha significantly

Table 5. Analysis of variance of tree diameter increment (TDI), tree volume increment (TVI), stand basal area increment, and total volume increment

Source of variation	Coalspur					Mercoal			
	D.F.	TDI	TVI	Basal area	Total volume	TDI	TVI	Basal area	Total volume
Factorial 0									
Block	2	8.46***	0.56	1.55	0.79	4.72*	1.25	2.63	2.19
N	1	18.45***	23.98	0.17	1.81	3.47	14.09***	3.20*	3.12
P	1	0.84	0.35	0.16	0.21	0.84	0.44	0.01	0.11
S	1	0.22	2.43	0.10	0.33	12.40***	4.77*	1.79	0.63
N × P	1	0.52	0.08	0.20	0.28	2.32	0.00	0.45	0.18
N × S	1	5.77*	0.98	0.73	0.15	0.14	0.28	0.11	0.24
P × S	1	1.28	0.58	1.94	2.12	0.08	0.52	0.01	0.08
Factorial 1									
Block	2	2.39	0.41	0.22	0.50	4.20*	1.93	1.17	3.25
N	1	10.52**	5.51*	1.29	2.00	0.05	1.30	0.18	0.09
P	1	2.23	0.09	5.54*	3.27	0.35	0.40	1.33	1.35
S	1	0.22	0.15	0.34	0.16	1.33	0.44	0.38	2.06
N × P	1	0.31	1.57	0.31	0.40	0.82	0.03	0.75	0.00
N × S	1	0.00	0.48	0.93	1.10	0.67	1.35	1.63	0.75
P × S	1	0.04	4.18*	0.35	0.79	0.67	0.16	0.08	0.00

* Significant at the 5% level.

** Significant at the 1% level.

*** Significant at the 0.1% level.

improved TVI (Table 6). High P and S in combination had an adverse effect on the TVI of the Coalspur stand (Fig. 2).

The beneficial effects of N and S on TVI of the Mercoal stand are also clearly shown in Table 6. On the unfertilized plots, TVI averaged 40.6 dm³. An addition of 188 kg/ha of N increased TVI to 49.5 dm³, or 22% over the control plots. TVI increased by 38% when 188 kg/ha of N and 94 kg/ha of P in combination were added and by 40% after the addition of 188 kg/ha of N, 94 kg/ha of P, and 56 kg/ha of S. The nonsignificance of N at the Factorial 1 level (Table 5), however, suggests that N deficiency on Mercoal soils was not as serious as that on Coalspur soils.

Stand increment

Assessment of fertilization effects on stand increment of these stands was difficult because these effects were confounded by mortality during the experimental period. Mortality rates, based on the number of stems per

hectare, ranged from 37 to 51% in the Coalspur stand and from 32 to 57% in the Mercoal stand.

Factorial analyses of stand increment data showed that N, P, and S fertilization had little effect on basal area and volume increments in Factorial 0 series on Coalspur soils and Factorial 1 series on Mercoal soils (Table 5). Nevertheless, N significantly improved the BA growth of the Mercoal stand in the Factorial 0 series, and P improved the BA growth of the Coalspur stand in the Factorial 1 series.

Table 6 shows 10-year stand BA and total volume increments on these two soils types by fertilization treatments. Periodic stand volume increment averaged 38.7 and 45.6 m³/ha for unfertilized plots on Coalspur and Mercoal soils, respectively. Despite high mortality, fertilizer treatments of 300 kg/ha of N, 150 kg/ha of P, and 23 kg/ha of S on Coalspur and 188 kg/ha of N on Mercoal soils significantly improved stand total volume by 20.5 and 28.0 m³/ha, or 53 and 61%, respectively, over the control. In other words, stand productivity could

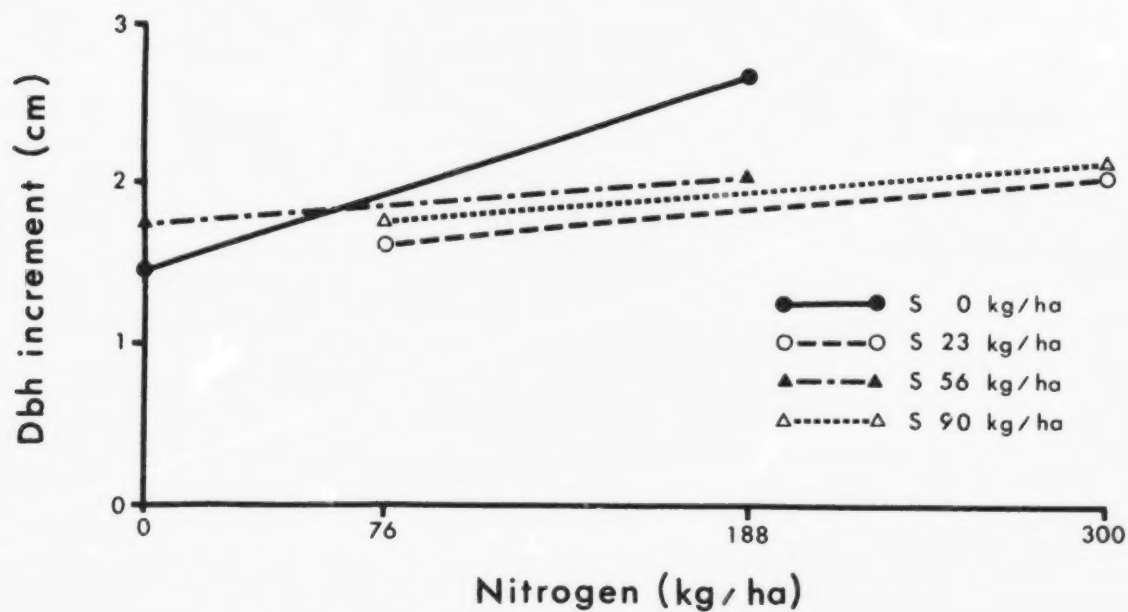


Figure 1. N $\times$ S interactions on TDI of trees on Coalspur soils.

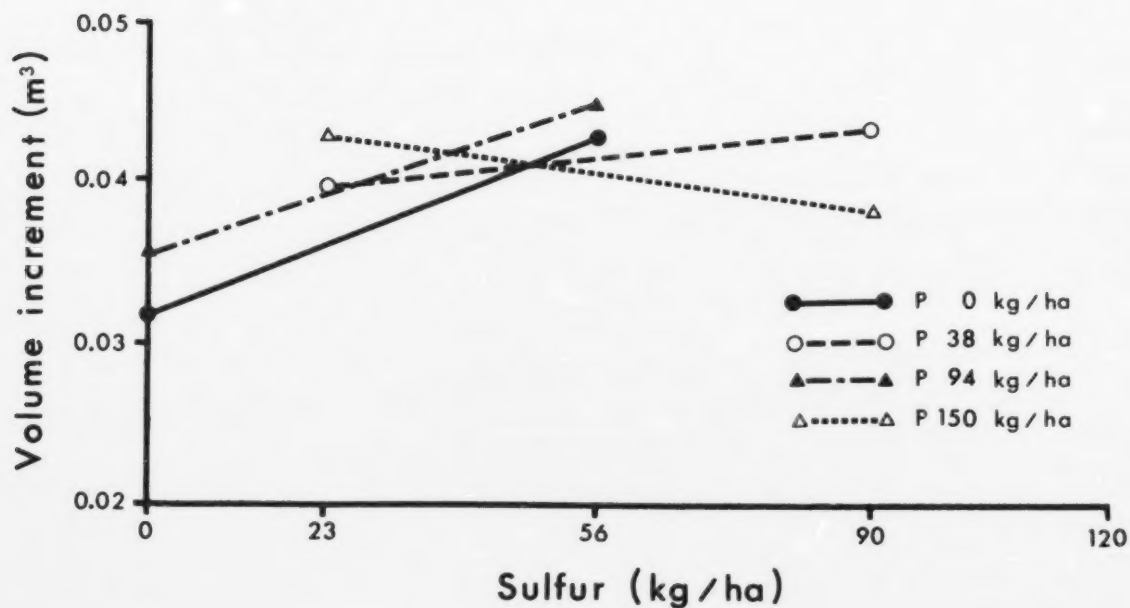


Figure 2. P $\times$ S interactions on TVI of trees on Coalspur soils.

Table 6. Ten-year tree diameter increment (TDI), tree volume increment (TVI), basal area increment, and total volume increment after different fertilizer treatments

Treatment	Coalspur				Mercoal			
	TDI (cm)	TVI (dm)	Basal area (m ² /ha)	Total volume (m ³ /ha)	TDI (cm)	TVI (dm)	Basal area (m ² /ha)	Total volume (m ³ /ha)
Factorial 0								
Control	1.25	30.6	14.65	38.70	1.58	40.6	12.30	45.59
N188	2.61***	44.1**	15.64	45.49	2.08	49.5	17.21	73.61*
P94	1.57	32.5	14.73	31.04	1.84	45.5	13.33	53.61
S56	1.69	32.5	11.44	30.87	2.52**	47.7	12.90	56.82
N188 P94	2.17**	43.2**	12.30	42.62	2.12	51.3	16.12	56.89
N188 S56	1.77	46.0**	13.26	43.97	2.23**	56.2**	12.02	47.19
P94 S56	1.86*	35.4	14.11	49.07	2.12	49.7	9.09	38.17
N188 P94 S56	2.09	43.1**	16.01	48.30	2.75**	57.0**	14.28	58.89
Factorial 1								
N76 P38 S23	1.86*	41.0*	13.28	37.11	2.54**	48.9	13.63	61.54
N300 P38 S23	2.14*	39.4*	16.43	49.16	2.36*	50.1	16.09	56.02
N76 P150 S23	1.47	39.5*	15.98	39.14	2.37*	52.5*	10.84	42.03
N300 P150 S23	2.06*	46.7***	18.38	59.19*	2.25*	51.7*	14.06	61.49
N76 P38 S90	1.82	40.8*	12.63	32.68	2.46**	50.1	14.48	62.97
N300 P38 S90	2.26*	45.6***	13.96	47.33	2.31*	53.9**	16.34	72.00
N76 P150 S90	1.66	36.7	17.63	51.13	2.59**	48.7	16.32	68.47
N300 P150 S90	2.03*	42.2**	16.75	52.66	2.95***	55.9**	11.62	52.58

* Treatment mean differs from control at the 5% level.

** Treatment mean differs from control at the 1% level.

*** Treatment mean differs from control at the 0.1% level.

potentially be improved by as much as 50% in these luvisols by appropriate fertilization.

Response to N, P, and S

This study confirmed that N improves lodgepole pine growth in various soil types as reported by Cochran (1975, 1979), Bella (1978), and Yang (1985). This nutrient significantly enhanced tree diameter and volume growth of the two 30-year-old stands on luvisols (Table 5). Despite the highly significant effects of N and S on diameter and volume growth of surviving trees on both soils, their effects on stand volume increment were not statistically significant. High mortality together with few replications might be the main reasons for this non-significance. Strong individual tree response but weak stand response suggest that the fertilizer may have effected a natural thinning. Consequently, to reduce mortality and to increase efficiency of fertilization, young dense lodgepole pine should be thinned before fertilization.

The need for extra N for tree growth differed between the two soil types; N consistently improved TDI and TVI on Coalspur soils at both factorial levels, while N improved only TVI on Mercoal soils at Factorial 0 levels. In other words, Coalspur soils are more deficient in N than Mercoal soils. These results were supported by pretreatment foliar analysis (Table 4). In contrast, soil analysis did not reveal the N requirement of trees on Coalspur soils; in fact, total N in both the Bt and C horizons of these soils was considerably higher than N in the corresponding Mercoal horizons (Table 3).

Lodgepole pine on these two soils responded differently to S fertilization. In the Factorial 0 series, S seemingly depressed TDI on Coalspur soils while it improved TDI and TVI of trees on Mercoal soils. These results agree with those from the 70-year-old stands (Yang 1983b). The beneficial N $\times$ S and N $\times$ P $\times$ S effects on TDI and TVI of the Mercoal stand (Table 6) are in line with results reported by Cochran (1978) and Will and Youngberg (1978) on ponderosa pine.

Cochran et al. (1979) maintain that a combination of 224 kg/ha of N and 34 kg/ha of S is a reasonable general application rate in the Pacific northwest for soils influenced by pumice and ash. The recommended rate is in good agreement with rates that produced the best TDI and TVI on Mercoal soils (Table 6).

A constant ratio of 0.030, the same ratio as that in foliar protein, is maintained between organic S and total N in the foliage of *Pinus* spp. (Kelly and Lambert 1972) and Douglas fir (Turner et al. 1977). Apparently N is taken up only at the rate at which S is available, and protein formation is limited by the amount of S. When S supply is adequate to balance the available N, the conifer accumulates excess S as sulfate, and protein formation proceeds at the rate at which N becomes available (Turner 1979). Consequently, an analysis of sulfate-S in the foliage is a more sensitive measure of available S than is foliar total S.

Luvissols formed on Cordilleran till and weathered sandstone in Alberta are reportedly deficient in S (Rennie 1974). This study indicates a beneficial effect of added S only on Mercoal soils. Whether the extremely acid Coalspur soil (Table 3) inhibits the uptake of the added S, or S content in the soil is sufficient for tree growth, warrants further investigations. An examination of foliar sulfate-S of trees on these two soils after S fertilization might explain the difference in growth response.

The effect of P on lodgepole pine growth was generally not significant in these luvissols; similar results were reported by Bella (1978). A depressive effect of P on the growth of spruce stands in northern Ontario has been reported (Morrison and Foster 1979; Payandeh 1982). In view of a general nonsignificant effect of P on TDI and TVI, the significant P effect on stand basal area increments of the Coalspur stand (Table 6) is likely an anomaly due to high mortality.

CONCLUSIONS

Fertilization with N and S significantly improved TDI and TVI of 30-year-old lodgepole pine on Coalspur and Mercoal soils in west-central Alberta. On Coalspur soils, N improved TDI and TVI for both experimental series; on Mercoal soils, fertilization effects were significant only in the Factorial 0 series where both N and S improved TVI, but only S improved TDI significantly. The greater response to N on the Coalspur stand agrees with pretreatment foliar analysis results.

On a stand volume basis, the effects of N and S fertilization were not statistically significant despite up to 60% improvement in stand total volume over unfertilized plots. These effects were probably obscured by mortality; therefore, for effective fertilization of young dense lodgepole pine stands, fertilizer should be used in combination with thinning. The cause of difference in growth response to S fertilization on these two soil types needs further studies.

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REFERENCES

- Bartlett, J.S. 1977. Growth response of fertilized Douglas-fir on Vancouver Island. M.S. thesis. Univ. Toronto, Toronto, Ont.
- Beaton, J.D.; Moss, A.; MacRae, I.; Kontin, J.W.; McPhee, W.P.T.; Kosick, R. 1965. Observation on foliage content of several coniferous tree species in British Columbia. *For. Chron.* 41:222-236.
- Beaton, J.D.; Tisdale, S.L.; Platou, J. 1971. Crop response to sulphur in North America. *Sulphur Inst. Tech. Bull.* 18.
- Bella, I.E. 1978. Fertilizing after thinning 70-year-old lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) in Alberta. *Can. For. Serv., Ottawa, Ont. Bi-mon. Res. Notes* 34(4):22-23.
- Boyd, W.D.; Lin, J.Y.; Strand, R.F. 1975. Results of a fertilizer screening trial in lodgepole pine. *Crown Zellerbach Corp., Cent. Res. Div. Memo* 623-2.

- Cochran, P.H. 1975. Response of pole-size lodgepole pine to fertilization. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Res. Note PNW-247.
- Cochran, P.H. 1978. Response of a pole-size ponderosa pine stand to nitrogen, phosphorus, and sulfur. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Res. Note PNW-319.
- Cochran, P.H. 1979. Response of thinned lodgepole pine after fertilization. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Res. Note PNW-385.
- Cochran, P.H.; Youngberg, C.T.; Steinbrenner, E.C.; Webster, S.R. 1979. Response of ponderosa pine and lodgepole pine to fertilization. Pages 89-94 in S.P. Gessel, R.M. Kenady, and W.A. Atkinson, eds. Proc. For. Fert. Conf. Univ. Wash., Coll. For. Res., For. Resour. Inst. Contrib. 40.
- Cochran, W.G.; Cox, G.M. 1957. Experimental design. 2nd edition. John Wiley and Sons, New York, N.Y.
- Dumanski, J.; Macyk, T.M.; Veauvy, C.F.; Lindsay, J.D. 1972. Soil survey and land evaluation of the Hinton-Edson area, Alberta. Alberta Inst. Pedol. Rep. S-72-31.
- Honer, T. 1967. Standard volume tables and merchantable conversion factors for the commercial tree species of central and eastern Canada. Can. Dep. For. Rural Dev., For. Branch, Ottawa, Ont. Inf. Rep. FMR-X-5.
- Johnstone, W.D. 1976. Variable-density yield tables for natural stands of lodgepole pine in Alberta. Dep. Fish. Environ., Can. For. Serv., Ottawa, Ont. Tech. Rep. 20.
- Kalra, Y.P. 1971. Methods used for soil, plant, and water analysis at soils laboratory of the Manitoba-Saskatchewan region, 1967-1970. Environ. Can., Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-11.
- Kelly, J.; Lambert, M.J. 1972. The relationship between sulfur and nitrogen in the foliage of *Pinus radiata*. Plant Soil 37:395-408.
- Miller, R.E.; Fight, R.D. 1979. Fertilizing Douglas-fir forests. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-83.
- Morrison, I.K.; Foster, N.W. 1979. Five-year growth in two nitrogen-phosphorus fertilization experiments in spruce and spruce-fir upland forest in northern Ontario. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont. Inf. Rep. O-X-299.
- Payandeh, B. 1982. Five-year growth response of northern Ontario peatland black spruce to fertilization and drainage. Environ. Can., Can. For. Serv., Great Lakes For. Res. Cent., Sault Ste. Marie, Ont. Inf. Rep. O-X-340.
- Rennie, P.J. 1974. Forest fertilization research in Canada. In Proceedings of a workshop on forest fertilization in Canada. Can. Dep. Environ., Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 5.
- Rowe, J.S. 1972. Forest regions of Canada. Environ. Can. Can. For. Serv., Ottawa, Ont. Publ. 1300.
- Smithers, L.A. 1961. Lodgepole pine in Alberta. Can. Dep. For., Ottawa, Ont. Bull. 127.
- Swan, H.S.D. 1972. Foliar nutrient concentrations in lodgepole pine as indicators of tree nutrient status and fertilizer requirement. Pulp Pap. Res. Inst. Can., Pointe Claire, Que. Woodlands Rep. WR 42.
- Turner, J. 1979. Interactions of sulfur with nitrogen in forest stands. Pages 116-125 in S.P. Gessel, R.M. Kenady, and W.A. Atkinson, eds. Proc. For. Fert. Conf. Univ. Wash., Coll. For. Res., For. Resour. Inst. Contrib. 40.
- Turner, J.; Lambert, M.J.; Gessel, S.P. 1977. Use of foliage sulphate concentrations to predict response to urea application by Douglas-fir. Can. J. For. Res. 7:476-480.
- Will, G.M.; Youngberg, C.T. 1978. Sulfur status of some central Oregon pumice soils. Soil Sci. Soc. Am. J. 42:132-134.
- Yang, R.C. 1983a. Composite design versus factorial experiments in forest fertilization trials. Can. J. For. Res. 13(3):438-444.
- Yang, R.C. 1983b. Natural lodgepole pine in west-central Alberta. Part III. Fertilization. Pages 15-19 in Lodgepole pine: regeneration and management, Proceedings of the 4th International Workshop. USDA For. Serv., Pac. Northwest For. Range Exp. Stn., Portland, Oreg. Gen. Tech. Rep. PNW-157.
- Yang, R.C. 1985. Ten-year growth response of 70-year-old lodgepole pine to fertilization in Alberta. Can. For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-266.